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Search for a light pseudoscalar Higgs boson in the boosted $\mu\mu\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for a light pseudoscalar Higgs boson (a) decaying from the 125 GeV (or a heavier) scalar Higgs boson (H) is performed using the 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, collected by the CMS experiment. The analysis considers gluon fusion and vector boson fusion production of the H, followed by the decay $\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau$, and considers pseudoscalar masses in the range $3.6 < m_{\mathrm{a}} < 21$ GeV. Because of the large mass difference between the H and the a bosons and the small masses of the a boson decay products, both the $\mu\mu$ and the $\tau\tau$ pairs have high Lorentz boost and are collimated. The $\tau\tau$ reconstruction efficiency is increased by modifying the standard technique for hadronic τ lepton decay reconstruction to account for a nearby muon. No significant signal is observed. Model-independent limits are set at 95% confidence level, as a function of m_{a}, on the branching fraction ($\mathcal{B}$) for $\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau$, down to $1.5\,(2.0) \times 10^{-4}$ for $m_{\mathrm{H}} = 125\,(300)$ GeV. Model-dependent limits on $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ are set within the context of two Higgs doublets plus singlet models, with the most stringent results obtained for Type-III models. These results extend current LHC searches for heavier a bosons that decay to resolved lepton pairs and provide the first such bounds for an H boson with a mass above 125 GeV.

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1 Introduction

Studies of the properties of the 125 GeV Higgs boson can be used to constrain models that include extended Higgs sectors beyond the standard model (SM) [1–5]. Examples include an extension of two Higgs doublets models (2HDM) [6] with a scalar singlet (2HDM+S) [7], the next-to-minimal supersymmetric SM (NMSSM) [8], and pure Higgs sector models containing additional Higgs fields [7]. Especially interesting are models with Higgs boson decay modes that are not detected in the standard channels, which focus on decays to SM particle pairs and invisible decay modes. A recent study by the CMS Collaboration [9] considers models where the Higgs sector contains only doublets and singlets, and the various couplings are otherwise free to vary with respect to their SM values. That analysis reports an upper limit of 0.47 on the branching fraction ($\mathcal{B}$) of the Higgs boson to undetected modes (that is, any mode besides $\gamma\gamma$, ZZ, WW, $\tau\tau$, and bb) at 95% confidence level (CL), when invisible modes are completely excluded. This upper limit on undetected modes strengthens as the upper limit on invisible modes weakens.

Given the weak limits on the branching fraction to undetected final states, it is important to explicitly explore all possibilities for unseen decay modes. Among the most prominent possibilities [10, 11] are decays of the type $\mathrm{H} \to \mathrm{aa}$ or $\mathrm{H} \to \mathrm{hh}$ [12], where H is a scalar Higgs boson and a (h) is a lighter pseudoscalar (scalar) Higgs boson. Such decays are possible in the SM extensions listed above, and generically have large branching fractions when kinematically allowed. However, such decays are not possible in the CP-conserving minimal supersymmetric SM (MSSM) [13]. In what follows, we refer to the light a and h bosons collectively as the a boson. The Higgs boson observed at 125 GeV can be either the lightest or second-lightest scalar [8]. Given observation of the 125 GeV Higgs boson, more recent theoretical studies [7, 14–27] consider the possible decays of this Higgs boson to a pair of lighter Higgs bosons. In all of these models (aside from the MSSM), it is possible for the lightest Higgs (pseudo)scalar boson to be much lighter than the SM-like Higgs boson. If the light Higgs boson is a scalar then the SM-like Higgs boson should be identified with the second-lightest scalar of the model. In the specific case of the NMSSM, a light pseudoscalar boson arises naturally when model parameters are chosen so that there is either a Peccei–Quinn or R global symmetry of the model [8, 10, 11]. Either symmetry will be spontaneously broken by the Higgs vacuum expectation values leading to a massless Nambu–Goldstone boson. After radiative corrections a nearly massless pseudoscalar, the a, emerges. Experimental search results are typically presented for four types of 2HDM (and thus 2HDM+S), differentiated by the couplings of SM fermions to the two doublet fields, Φ_1 and Φ_2, and by their dependence on the ratio of vacuum expectations for the two Higgs doublets, $\tan\beta$. In particular, the NMSSM corresponds to Type-II 2HDM+S, while for Type-III 2HDM+S only the charged leptons couple to Φ_1, which yields enhanced rates, especially at large values of $\tan\beta$. We note that in searches performed so far, the event selection and detection efficiencies for the hh case are essentially the same as for aa. In addition, the branching fractions for h decays are nearly the same as for a decays. Finally, the possibility of additional scalar Higgs bosons with masses above 125 GeV is motivated in generic 2HDM+S [7, 28].

Limits from the CERN LEP experiments on the production of a light scalar boson [29–31] are evaded if the h is singlet-dominated, as required in the limit where the 125 GeV state is SM-like [21, 27, 32]. LEP2 limits on a scalar boson decaying to two light pseudoscalars are obtained for Higgs boson mass (m_{H}) less than 107 GeV [33]. Several searches for different scenarios involving light (pseudo)scalar bosons have been performed by the CERN LHC experiments. The CMS [34] (based on Ref. [35]) and LHCb [36] Collaborations place limits on the proton-proton (pp) production of a light pseudoscalar decaying to $\mu\mu$, $\sigma(\mathrm{pp} \to \mathrm{a})\mathcal{B}(\mathrm{a} \to \mu\mu)$, that significantly constrain the MSSM-like fraction of the NMSSM pseudoscalar state, especially at large $\tan\beta$. Nonetheless, large $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ remains possible. Direct constraints on $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ are obtained by CMS [37] and ATLAS [38] based on the 4μ final state and by CMS [39] using the $\mu\mu\tau\tau$, 4τ, and $\mu\mu$bb final states. Analyses especially relevant for pseudoscalar masses, m_{a}, greater than twice the τ lepton mass, m_{τ}, are based on the $\mu\mu\tau\tau$, bb$\tau\tau$, 4τ, and 4b final states and have been performed by the CMS [40–42] and ATLAS [43–45] Collaborations.

The analysis presented in this paper considers $\mu\mu\tau\tau$ final states arising from $\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau$, where SM-like production of the H boson via the dominant gluon fusion (ggF) and vector boson fusion (VBF) modes are both included [46]. This analysis focuses on the pseudoscalar boson mass range 3.6–21 GeV, complementary to searches, such as Ref. [40], that focus on heavier pseudoscalar masses. For light masses, the large Lorentz boost of the a boson causes its decay products to overlap. In the $\mu\mu$ channel, the standard CMS muon identification has sensitivity to the topology of boosted muon pairs similar to that for an isolated, nonboosted muon pair. To reconstruct the collimated τ lepton pair, we have developed a boosted τ lepton pair reconstruction technique to target the specific decay where one τ lepton decays to a muon and neutrinos, τ_{μ}, while the other decays to one or more hadrons and a neutrino, τ_{h}, thus: $\mathrm{a} \to \tau_{\mu}\tau_{\mathrm{h}}$. This technique improves upon the standard CMS τ lepton reconstruction that is optimized for isolated, nonboosted τ leptons. The $\mu\mu\tau_{\mu}\tau_{\mathrm{h}}$ channel has greater detection efficiency than final states with b quarks, which are difficult to reconstruct at low momentum and significant boost, and has a larger branching fraction than most models with four-muon final states. The effectiveness of this improved technique also makes possible for the first time the search for the decays of a heavier Higgs boson to aa in the $\mu\mu\tau\tau$ final state at low m_{a}, with $m_{\mathrm{H}} = 300\,\mathrm{GeV}$ used as a demonstration. Such an H boson generically has a large branching fraction to any kinematically accessible pair of lighter bosons [28, 47]; the light bosons are highly boosted and the resulting final-state leptons are similarly collimated. The search is performed using an unbinned parameterized maximum likelihood fit of signal and background contributions to the two-dimensional (2D) distribution of the $\mu\mu$ invariant mass $m(\mu\mu)$ and the 4-body visible mass $m(\mu\mu\tau_{\mu}\tau_{\mathrm{h}})$.

This paper is organized as follows. A brief description of the CMS detector is given in Section 2. Section 3 summarizes the data and simulated samples used. Section 4 describes the object identification algorithms, including the modified $\tau_{\mu}\tau_{\mathrm{h}}$ reconstruction technique, while Section 5 focusses on the event selection. The background and signal models of the 2D unbinned fit are described in Section 6 and the treatment of systematic uncertainties are subsequently discussed in Section 7. The model-independent results, as well as interpretation in the context of several 2HDM+S types, are presented in Section 8. The paper is summarized in Section 9.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [48]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [49].

3 Data and simulated samples

This search uses a sample of pp collisions at the LHC, collected in 2016 at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$.

The acceptance and reconstruction efficiency of the $\text{H} \to \text{aa} \to \mu\mu\tau\tau$ processes are evaluated using simulated events. These signal processes are generated with MADGRAPH5_aMC@NLO version 2.2.2 [50] at next-to-leading order (NLO). The PYTHIA 8.205 program [51] is used for parton showering, hadronization, and the underlying event is simulated with the CUETP8M1 tune [52]. The NNPDF3.0 [53] set of parton distribution functions is used. Samples are generated for $3.6 < m_\text{a} < 21\,\text{GeV}$ for the SM-like H boson with $m_\text{H} = 125\,\text{GeV}$, and for $5 < m_\text{a} < 21\,\text{GeV}$ for a heavier H boson with $m_\text{H} = 300\,\text{GeV}$. The ggF Higgs production process is simulated for each sample with the obtained signal yields scaled to the sum of the expected events from ggF and VBF processes. The VBF Higgs production process is simulated for a subset of the H and a boson mass pairs. The inclusion of the VBF process increases the expected signal yield by 8 (19)% for $m_\text{H} = 125\,(300)$ GeV. An acceptance correction arising from a small difference in the analysis acceptance for ggF and VBF events of 0.5–3.0% is applied as a function of Higgs and pseudoscalar boson masses, with an uncertainty of 0.5%. This correction primarily arises from the differences in transverse momentum p_T spectrum of the generated H and a bosons. These differences have a negligible effect on the shapes of the reconstructed pseudoscalar mass distributions that are used to discriminate signal from background. The WH, ZH, and $\text{t}\bar{\text{t}}\text{H}$ Higgs boson production modes do not significantly increase the sensitivity of this search due to lower cross sections and reduced acceptance and are not included.

For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [54], and the event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing (pileup) and are weighted so that the multiplicity distribution matches the measured one, with an average of about 23 interactions per bunch crossing.

4 Event reconstruction

Using the information from all CMS subdetectors, a particle-flow (PF) technique is employed to identify and reconstruct the individual particles emerging from each collision [55]. The particles are classified into mutually exclusive categories: charged and neutral hadrons, photons, muons, and electrons. Jets and τ_h candidates are identified algorithmically using the PF-reconstructed particles as inputs. The missing transverse momentum vector $\vec{p}_\text{T}^\text{miss}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF objects in an event. Its magnitude is referred to as p_T^miss. The primary pp interaction vertex is defined as the reconstructed vertex with the largest value of summed physics-object p_T^2. The physics objects considered in the vertex determination are the objects returned by a jet finding algorithm [56, 57] applied to all charged tracks associated with the vertex, plus the corresponding associated p_T^miss, taken as the negative vector sum of the p_T of those jets. Finally, additional identification criteria are applied to the reconstructed muons, electrons, photons, τ_h candidates, jets, and p_T^{miss} to reduce the frequency of misidentified objects. This section details the reconstruction and identification of muons, jets, and τ_h candidates.

4.1 Muons

Muons are reconstructed within $|\eta(\mu)| < 2.4$ [58]. The reconstruction combines the information from both the tracker and the muon spectrometer. The muons are selected from among the reconstructed muon track candidates by applying minimal requirements on the track components in the muon system and taking into account matching with small energy deposits in the calorimeters. For each muon track, the distance of closest approach to the primary vertex in the transverse plane is required to be less than 0.2 cm. The distance of closest approach to the primary vertex along the beamline, d_z, must be less than 0.5 cm.

The isolation of individual muons is defined relative to their transverse momentum $p_T(\mu)$ by summing over the p_T of charged hadrons and neutral particles within a cone around the muon direction at the interaction vertex with radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ (where ϕ is the azimuthal angle in radians) :

$$I^{\mu} = \left(\sum p_T^{\text{charged}} + \max\left[0, \sum p_T^{\text{neutral}} + \sum p_T^{\gamma} - p_T^{\text{PU}}\right]\right) / p_T(\mu). \tag{1}$$

Here, $\sum p_T^{\text{charged}}$ is the scalar p_T sum of charged hadrons originating from the primary vertex. The $\sum p_T^{\text{neutral}}$ and $\sum p_T^{\gamma}$ are the scalar p_T sums for neutral hadrons and photons, respectively. The neutral contribution to the isolation from pileup interactions, p_T^{PU}, is estimated as $0.5 \sum_i p_T^{\text{PU},i}$, where i runs over the charged hadrons originating from pileup vertices and the factor 0.5 corrects for the ratio of charged to neutral particle contributions in the isolation cone. Muons are considered isolated if $I^{\mu} < 0.25$.

4.2 Jets

Jets are reconstructed using PF objects. The anti-k_T jet clustering algorithm [56, 57] with a distance parameter of 0.4 is used. The standard method for jet energy corrections [59] is applied. In order to reject jets coming from pileup collisions, a multivariate (MVA) jet identification algorithm [60] is applied. This algorithm takes advantage of differences in the shapes of energy deposits in a jet cone between pileup jets and jets originating from a quark or gluon. The combined secondary vertices (CSV) b tagging algorithm [61] is used to identify jets originating from b hadrons [62]. The efficiency for tagging b jets is $\approx$63%, while the misidentification probability for charm (light-quark or gluon) jets is $\approx$12 (1)%.

4.3 Hadronic τ lepton decays

Hadronically decaying τ leptons are reconstructed and identified within $|\eta(\tau_h)| < 2.3$ using the hadron-plus-strips (HPS) algorithm [63], which targets the main decay modes by selecting PF objects with one charged hadron and up to two neutral pions, or with three charged hadrons. The HPS algorithm is seeded by the jets described in Section 4.2. The τ_h candidates are reconstructed based on the number of tracks and on the number of ECAL strips with an energy deposit in the η-ϕ plane.

This analysis uses a specialized $\tau_\mu\tau_h$ reconstruction algorithm, which uses the same HPS method as the above, with a modified jet seed. This method is designed to reconstruct boosted $\tau_\mu\tau_h$ objects, for which the τ lepton decaying leptonically to a muon overlaps with the hadronic decay products of the other τ lepton. One τ lepton is required to decay to a muon because this mode has a high reconstruction efficiency and a low misidentification probability. As in Ref. [39], a joint reconstruction of the τ_{h} candidate and a nearby muon is performed. Jets that seed the τ_{h} reconstruction are first modified to remove muons with $p_{\mathrm{T}} > 3\,\mathrm{GeV}$ passing minimal identification requirements from their jet constituents. The τ_{h} candidates reconstructed using these modified jets are required to have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, where the reconstructed $p_{\mathrm{T}}(\tau_{\mathrm{h}})$ corresponds to the visible portion of the τ lepton decay. To reject τ_{h} candidates that arise from constituents not originating from the primary vertex, the τ_{h} candidates must have $d_z < 0.5\,\mathrm{cm}$. To reduce background contribution from jets arising from b quarks, the jet seeds to the τ_{h} reconstruction must additionally fail the CSV jet tagging algorithm. Because no MVA discriminant to reject electrons [63] is applied, the τ_{h} reconstruction algorithm has high efficiency to select τ leptons that decay to electrons, τ_{e}. The fraction of reconstructed τ_{h} candidates that are τ_{e} decays is estimated from simulation to be 18–22%, predominantly reconstructed in the one-prong decay mode with no additional neutral hadrons. No distinction is made between τ_{e} and τ_{h} candidates and this paper refers to the contribution of both decay categories as τ_{h} candidates.

The full $\tau_\mu\tau_{\mathrm{h}}$ identification procedure includes the modified HPS algorithm described above, along with a requirement on the τ_{h} candidate isolation. The isolation of a τ_{h} candidate is computed using an MVA discriminant [63]. The discriminant is computed using PF candidates, with the overlapping muon excluded, in the region around the τ_{h} candidate defined by $\Delta R < 0.8$. The τ_{h} candidates are required to pass a selection on the MVA discriminant output as a function of $p_{\mathrm{T}}(\tau_{\mathrm{h}})$ to yield an approximately constant efficiency of $\approx$80%. No discriminant to reject muons [63] is applied, as it would reduce the reconstruction efficiency of the boosted $\tau_\mu\tau_{\mathrm{h}}$ final state.

4.4 Charged lepton efficiency

The combined efficiencies of the reconstruction, identification, and isolation requirements for muons are measured in several bins of $p_{\mathrm{T}}(\mu)$ and $|\eta(\mu)|$ using a "tag-and-probe" technique [64] applied to an inclusive sample of muon pairs from Z boson and J/ψ meson events [58]. These efficiencies are measured in data and simulation. The data to simulation efficiency ratios are used as scale factors to correct the simulated event yields. For τ_{h} candidates, two scale factors are similarly measured using a $\mathrm{Z} \to \tau_\mu\tau_{\mathrm{h}}$ sample [63] to be 0.60 ± 0.11 (0.97 ± 0.05) for $10 < p_{\mathrm{T}}(\tau_{\mathrm{h}}) < 20\,\mathrm{GeV}$ ($p_{\mathrm{T}}(\tau_{\mathrm{h}}) > 20\,\mathrm{GeV}$), which are found to be independent of $|\eta(\tau_{\mathrm{h}})|$. For $10 < p_{\mathrm{T}}(\tau_{\mathrm{h}}) < 20\,\mathrm{GeV}$, the $\mathrm{Z} \to \tau_\mu\tau_{\mathrm{h}}$ data sample contains significant W+jets background, making the scale factor difficult to estimate with as high a precision as for $p_{\mathrm{T}}(\tau_{\mathrm{h}}) > 20\,\mathrm{GeV}$.

5 Event selection

Collision events are selected by a trigger that requires the presence of an isolated muon with $p_{\mathrm{T}} > 24\,\mathrm{GeV}$ [48]. Trigger efficiencies are measured in data and simulation using the tag-and-probe technique. The event is required to have two isolated opposite-sign muons with $\Delta R < 1$. The leading muon which is matched to the muon that triggered the event must have $p_{\mathrm{T}} > 26\,\mathrm{GeV}$. The second muon must have $p_{\mathrm{T}} > 3\,\mathrm{GeV}$. These muons constitute a $\mu\mu$ pair from one of the pseudoscalar candidates.

The second pseudoscalar is selected via its decay to an isolated opposite-sign $\tau_\mu\tau_{\mathrm{h}}$ pair. The $\tau_\mu\tau_{\mathrm{h}}$ selection requires one identified muon with $p_{\mathrm{T}} > 3\,\mathrm{GeV}$, with no isolation selection imposed, and one τ_{h} candidate with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, reconstructed as described in Section 4.3. The reconstructed muon corresponds to the visible portion of the τ_μ decay. The two τ lepton can-

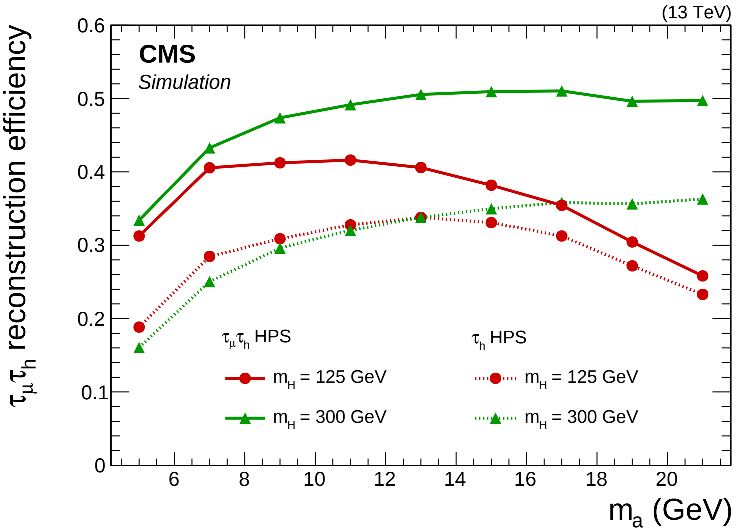

Figure 1: The efficiency of the standard HPS (dashed lines) and $\tau_\mu\tau_\mathrm{h}$ HPS reconstruction used in this search (solid lines) as a function of pseudoscalar boson mass for $m_\mathrm{H} = 125$ (red) and 300 GeV (green). The events are required to have two reconstructed muons passing identification and isolation criteria. The efficiency is measured by additionally requiring a third muon passing identification requirements and a τ_h candidate reconstructed using either the standard HPS algorithm or the $\tau_\mu\tau_\mathrm{h}$ HPS algorithm and passing isolation requirements.

didates are required to lie within $\Delta R(\tau_\mu, \tau_\mathrm{h}) < 0.8$. The value of 0.8 is driven by the modified HPS algorithm isolation discriminant and ensures the boosted topology. This selection, with the corresponding selection of the $\mu\mu$ pair, prevents combinatoric background in which the wrong combination of leptons is assigned to the pseudoscalar candidates. The $\mu\mu$ pair selection is looser to avoid loss of efficiency.

The modified $\tau_\mu\tau_\mathrm{h}$ reconstruction and identification algorithm increases the signal efficiency throughout the full range of Higgs boson and pseudoscalar hypotheses considered, as shown in Fig. 1. The efficiency of the $\tau_\mu\tau_\mathrm{h}$ reconstruction and identification is measured by requiring the presence of a muon passing the identification requirements and a τ_h candidate passing either the standard τ_h HPS reconstruction or the $\tau_\mu\tau_\mathrm{h}$ HPS reconstruction, as well as the MVA isolation discriminant. The increase in efficiency arises incrementally both from the modification of the jets which seed the $\tau_\mu\tau_\mathrm{h}$ reconstruction and the exclusion of the muon energy from the MVA isolation discriminant. Because of the increase in Lorentz boost, the jet seed modification is the primary cause of increased efficiency at low m_a where the pseudoscalar decay products are most overlapping, with $\Delta R(\tau_\mu, \tau_\mathrm{h}) < 0.4$. At larger separation, $0.4 < \Delta R(\tau_\mu, \tau_\mathrm{h}) < 0.8$, the change in the MVA discriminant becomes the only source of efficiency increase. The reduced efficiency at low pseudoscalar mass is due to the high Lorentz boost in which the muon is nearly collinear with a charged hadron from the τ_h candidate. At low Lorentz boost, the muon and τ_h candidate have a large separation. In this case, the efficiency is reduced from the requirement of the boosted topology, especially at $m_\mathrm{H} = 125$ GeV. The efficiency for the higher H boson mass is less affected by an increase in pseudoscalar mass because the reduction in Lorentz boost is generally not significant enough to separate the τ leptons from a pseudoscalar decay beyond the selection requirement of $\Delta R(\tau_\mu, \tau_\mathrm{h}) < 0.8$.

6 Signal and background modeling

The main source of background in this search is Drell–Yan $\mu\mu$ production in association with at least one jet that is misidentified as the $\tau_\mu\tau_h$ candidate. This background, reduced by the $\tau_\mu\tau_h$ reconstruction, features the prominent $\mu\mu$ resonances with masses between 3.6 and 21 GeV: ψ(2S) (3.69 GeV), Υ(1S) (9.46 GeV), Υ(2S) (10.0 GeV), and Υ(3S) (10.4 GeV) [65]. In the $m(\mu\mu)$ distribution, the known resonance peaks appear on top of the Drell–Yan continuum. In the $m(\mu\mu\tau_\mu\tau_h)$ distribution, the $\mu\mu$ + jet background appears as an exponentially falling distribution with a threshold around 40–60 GeV because of the p_T thresholds of the three reconstructed muons and one τ_h candidate. The signal is characterized by a narrow $m(\mu\mu)$ resonance from a pseudoscalar decay and a broader $m(\mu\mu\tau_\mu\tau_h)$ distribution because of the invisible decay products of one of the pseudoscalar Higgs bosons. As described below, the search strategy consists of an unbinned fit of $m(\mu\mu)$ vs. $m(\mu\mu\tau_\mu\tau_h)$, using analytical models for the signal and background shapes in each dimension. The background shape model for the Drell–Yan continuum, the meson resonances mentioned above, and additionally the J/ψ resonance (3.10 GeV [65]) are constrained via a data control region enriched in $\mu\mu$+jet events. Although the J/ψ resonance falls outside the kinematically allowed search window for a $\tau\tau$ resonance, it is modeled in the fit to provide a better background description near the ψ(2S) meson.

The analysis uses a simultaneous unbinned fit of three mutually exclusive regions to model the background and search for a signal. The "control region" requires the presence of two muons and no identified $\tau_\mu\tau_h$ candidate. The next two regions additionally require a reconstructed $\tau_\mu\tau_h$ candidate and are defined by passing or failing the τ_h MVA isolation requirement, labeled as "signal region" and "sideband", respectively. A schematic depiction of the three regions is shown in Fig. 2. Two additional regions are also shown and are used to validate the background estimation method described below.

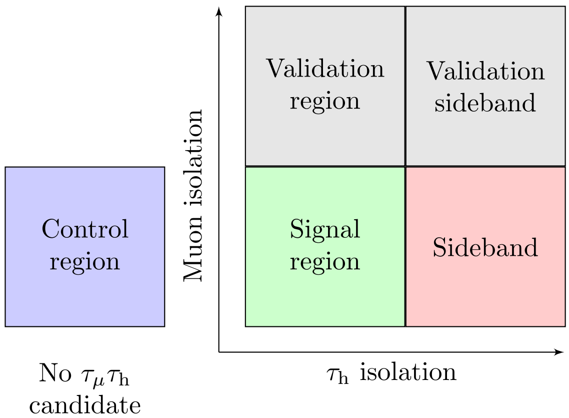

Figure 2: Schematic of the fit regions in the analysis. Events with two isolated muons and no $\tau_\mu\tau_h$ candidates constitute the control region (blue). Events that have a $\tau_\mu\tau_h$ candidate are further divided based on the isolation of the τ_h candidate with isolated $\tau_\mu\tau_h$ candidates forming the signal region (green) and the remaining $\tau_\mu\tau_h$ candidates forming the sideband (red). Additionally, the $\mu\mu$ candidates that fail the muon isolation selection form two analogous regions for the validation of the background fit model (gray).

The choice of $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_h)$ as observables for distinguishing the $H \to aa$ signal from the SM background processes is found to be more performant than combinations including $m(\tau_\mu\tau_h)$ over the largest range of Higgs boson and pseudoscalar mass hypotheses. The signal is modeled as a 2D function given by the product of a Voigt function for $m(\mu\mu)$ and a split normal distribution for $m(\mu\mu\tau_\mu\tau_h)$. For the signal processes, there is minimal correlation between the $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ distributions. The parameters of the model are determined from fits to the signal simulation. Each generated distribution, with a specified Higgs boson and pseudoscalar mass, is fit with the described 2D function. For each parameter, a polynomial function is used to interpolate between the generated masses: a first-order polynomial for the mean value of the $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_\mathrm{h})$, a second-order polynomial for each width parameter, and the product of a first-order polynomial and two error functions for the signal normalization. The search is performed for pseudoscalar masses between 3.6 and 21 GeV.

The 2D fit of $m(\mu\mu)$ vs. $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ is performed in data to model the SM background processes and extract any significant signal process contribution in three ranges of the $m(\mu\mu)$ spectrum: $2.5 < m(\mu\mu) < 8.5\,\mathrm{GeV}$, $6 < m(\mu\mu) < 14\,\mathrm{GeV}$, and $11 < m(\mu\mu) < 25\,\mathrm{GeV}$. For a given m_a, a single $m(\mu\mu)$ range is used, with the transition between the $m(\mu\mu)$ ranges occurring at $m_\mathrm{a} = 8$ and 11.5 GeV. There is some overlap in the fit ranges to allow the lower or upper portion of the signal model to be fully contained in the given fit range. The background probability density function (PDF) used for the $m(\mu\mu)$ spectrum is the sum of an exponential together with two, three, or zero Voigt distributions to model the SM resonances for the three respective ranges. An additional exponential function is necessary to model the rising continuum background near the J/ψ resonance in the lowest $m(\mu\mu)$ range. The $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ background distribution is modeled with the product of an error function and the sum of two exponential distributions. The second exponential provides the fit with additional flexibility to allow the fit to favor an extended tail if necessary. The fit range is $0 < m(\mu\mu\tau_\mu\tau_\mathrm{h}) < 1200\,\mathrm{GeV}$ in all three $m(\mu\mu)$ ranges. The $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ functions are multiplied together to produce a 2D PDF. Because $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ is loosely correlated with $m(\mu\mu)$ in the background distribution, the parameters of the $m(\mu\mu\tau_\mu\tau_\mathrm{h})$ background model in a given $m(\mu\mu)$ range are allowed to vary independently of the other ranges, allowing a correlation between $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_\mathrm{h})$.

The normalization of the background model in the signal region is estimated from the sideband using a "tight-to-loose" method. This method uses a $\mathrm{Z}(\mu\mu) + \mathrm{jet}$ sample to estimate the efficiency for a jet that has passed all the τ_h reconstruction requirements (including the muon removal step) of Section 4.3, except the MVA isolation requirement, to additionally pass the MVA isolation requirement. The region contains events collected with a single muon trigger with the requirement of two isolated opposite-sign muons and a jet that has been misidentified as a $\tau_\mu\tau_\mathrm{h}$ object with a muon within $\Delta R(\tau_\mu, \tau_\mathrm{h}) < 0.8$, without the requirement on the MVA isolation. The $\mu\mu$ pair must have invariant mass $81 < m(\mu\mu) < 101\,\mathrm{GeV}$. The tight-to-loose ratio, f, is defined as the ratio of the number of τ_h candidates that pass the MVA isolation requirement in addition to the other identification requirements (the "tight" condition) to the number of τ_h candidates that pass the other identification requirements, but with a relaxed requirement on the isolation (the "loose" condition). The calculation of f is performed separately for each hadronic decay mode of the τ lepton and is binned in $p_\mathrm{T}(\tau_\mathrm{h})$. This region is dominated by Drell–Yan events containing jets. Residual contributions from diboson processes, as estimated from simulation, are subtracted from the data. The associated jets are the objects most likely to pass the τ_h reconstruction criteria. This tight-to-loose ratio is measured to be 10–40%, increasing at lower $p_\mathrm{T}(\tau_\mathrm{h})$. In general, the decay mode with three charged tracks has a lower tight-to-loose ratio than those with a single charged track.

The sideband is then reweighted using the tight-to-loose method to estimate the contribution in the signal region. The weights are applied on an event-by-event basis as a function of $p_\mathrm{T}(\tau_\mathrm{h})$. The tight-to-loose method is verified in a validation region independent of the analysis region by inverting the isolation requirement on the muon in the $\mu\mu$ pair that did not trigger the event. These regions correspond to the gray boxes in Fig. 2. The expected and observed yields in this validation region are compatible within 15%, and an uncertainty is derived from this value.

The parameters of the $\mu\mu$ resonances—mean (μ), width (Γ), and resolution (σ)—and the relative normalizations—N_i/N_j where i and j are a pair of background resonances—between the J/ψ and $\psi(2S)$ resonances and between the $\Upsilon(1S)$ and each of the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances are constrained via a simultaneous fit among all three regions. The parameters of the resonances are compatible, and thus the same, among the three regions, while their relative normalizations are only the same in the sideband and control region with the signal region relative normalizations related to the sideband via a linear transformation. The slope and constant values of this linear transformation are determined from a fit to the sideband and the tight-to-loose estimation of the background in the signal region. An uncertainty is assigned for this linear constraint in the signal region. This uncertainty is derived in a validation region and a corresponding validation sideband in which the muon of the $\mu\mu$ pair which did not trigger the event has an inverted isolation requirement and is measured to be 5–20% depending on the resonance. The parameters of the $\mu\mu$ continuum ($\lambda^i_{\mu\mu}$), the $m(\mu\mu\tau_\mu\tau_h)$ continuum ($\lambda^i_{\mu\mu\tau\tau}$), the $m(\mu\mu\tau_\mu\tau_h)$ error function shift (erf_a) and scale (erf_b), and the relative normalizations of the $\mu\mu$ resonances to the $\mu\mu$ continuum ($N_{\Upsilon(1S)}/N_{J/\psi}$ and $N_{J/\psi}/N_{\mathrm{continuum}}$) are constrained in the signal region to the sideband via the tight-to-loose method. All remaining parameters are free to vary independently of each other and share no constraint between regions. Table 1 summarizes these constraints.

Table 1: Background model parameters and their relations among the three fit regions in the analysis. The $\mu\mu$ background model includes the five meson resonances modeled using a Voigt function over an exponential continuum. The 4-body background model includes an error function multiplied with the sum of two exponential distributions. Three types of fit region relations are used: (a) constrained, in which the parameters are the same in the indicated regions, (b) free, in which the parameter is not related to those in any other region, and (c) related via the $\tau_\mu\tau_h$ tight-to-loose ratio, in which the indicated parameter in the signal region is constrained to the corresponding parameter in the sideband via a linear transformation.

Category	Parameters	Signal region	Sideband	Control region
$\mu\mu$ resonances	μ, σ, Γ	Constrained (three regions)		
$\mu\mu$ continuum	$\lambda^{\mathrm{i}}_{\mu\mu}$	Tight-to-loose	Free	Free
$\mu\mu\tau_\mu\tau_h$	Erf_a, Erf_b, $\lambda^{\mathrm{i}}_{\mu\mu\tau\tau}$	Tight-to-loose	Free	—
Normalizations	$N_{\psi(2S)}/N_{J/\psi}$	Tight-to-loose	Constrained (two regions)	
	$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}$	Tight-to-loose	Constrained (two regions)	
	$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}$	Tight-to-loose	Constrained (two regions)	
	$N_{\Upsilon(1S)}/N_{J/\psi}$	Tight-to-loose	Free	Free
	$N_{J/\psi}/N_{\mathrm{continuum}}$	Tight-to-loose	Free	Free

The background model and observed data in the control region are shown in Fig. 3. Projections on the $m(\mu\mu)$ and $m(\mu\mu\tau_\mu\tau_h)$ axes of the 2D background model and observed data with sample signal distributions for each fit range are shown in Figs. 4 and 5 for the sideband and signal region, respectively. The signal distribution is scaled assuming an SM Higgs boson production cross section [46] and $\mathcal{B}(\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau) = 5 \times 10^{-4}$. A small level of signal contamination is expected in the sideband and is included in the fit. For the signal processes, there is minimal correlation between the $m(\mu\mu)$ and the $m(\mu\mu\tau_\mu\tau_h)$ distributions.

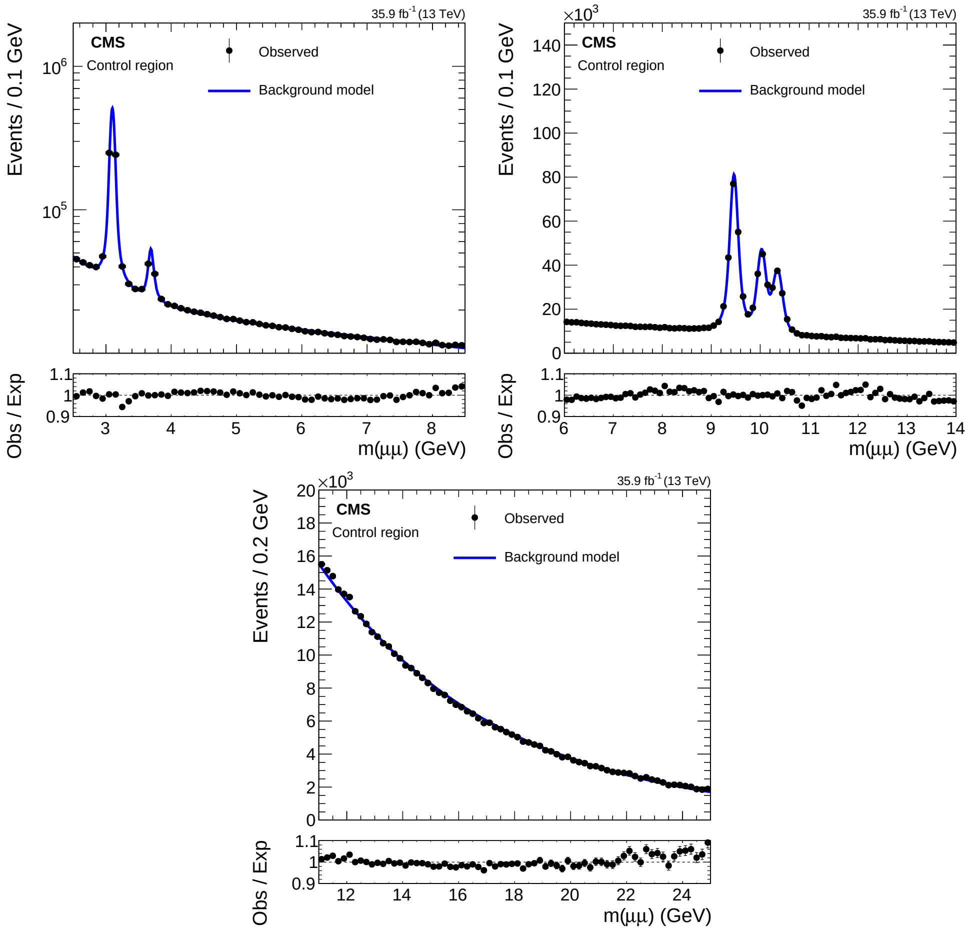

Figure 3: Background model fits and observed data in the control region $m(\mu\mu)$ distribution. The figures are divided into three fit ranges: $2.5 < m(\mu\mu) < 8.5\,\mathrm{GeV}$ (upper-left), $6 < m(\mu\mu) < 14\,\mathrm{GeV}$ (upper-right), and $11 < m(\mu\mu) < 25\,\mathrm{GeV}$ (lower).

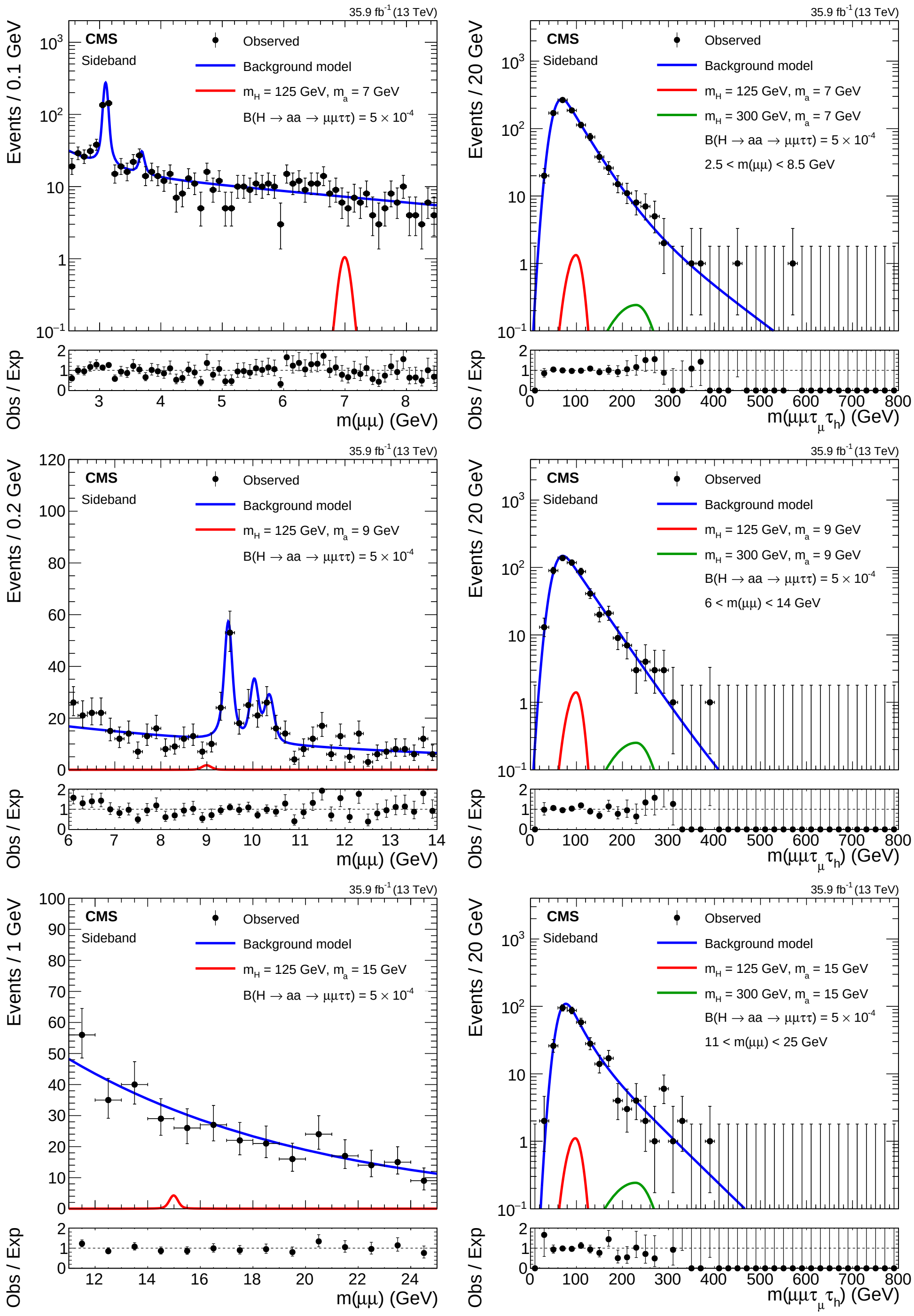

Figure 4: Projections of 2D background model fits and observed data in the sideband on the $m(\mu\mu)$ (left), and $m(\mu\mu\tau_\mu\tau_h)$ (right) axes with sample signal distributions that assume H boson masses of $m_H = 125$ and 300 GeV. The figures are divided into three fit ranges: $2.5 < m(\mu\mu) < 8.5$ GeV (upper), $6 < m(\mu\mu) < 14$ GeV (middle), and $11 < m(\mu\mu) < 25$ GeV (lower).

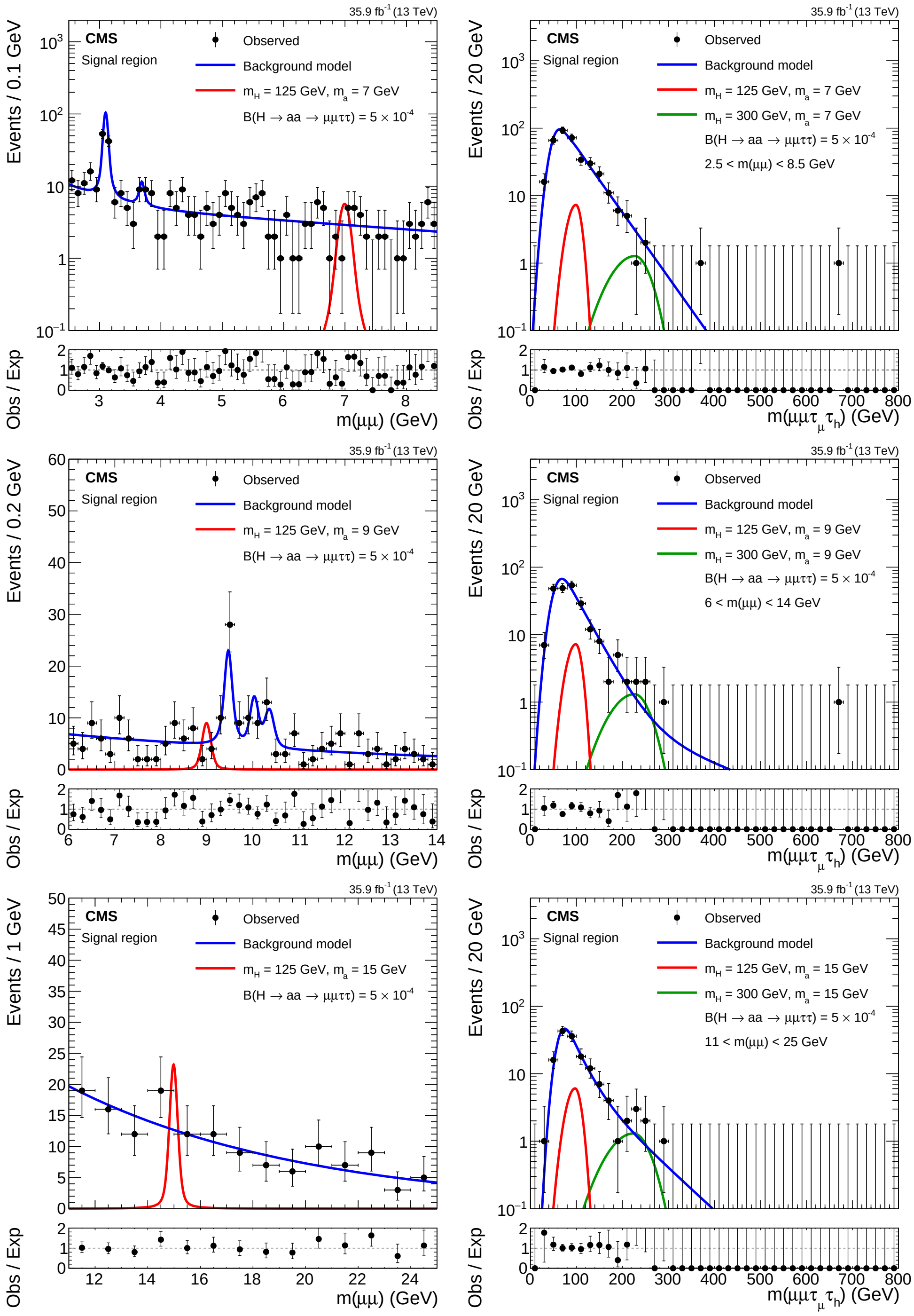

Figure 5: Projections of 2D background model fits and observed data in the signal region on the $m(\mu\mu)$ (left), and $m(\mu\mu\tau_\mu\tau_h)$ (right) axes with sample signal distributions that assume H boson masses of $m_H = 125$ and 300 GeV. The figures are divided into three fit ranges: $2.5 < m(\mu\mu) < 8.5$ GeV (upper), $6 < m(\mu\mu) < 14$ GeV (middle), and $11 < m(\mu\mu) < 25$ GeV (lower).

7 Systematic uncertainties

Uncertainties in the signal process modeling contribute both to the total expected signal yield and the individual signal fit parameters. Despite the small spatial separation between the τ_μ and τ_h candidates, the $\tau_\mu\tau_h$ reconstruction procedure, which relies on the excellent muon discrimination of the CMS detector, allows the uncertainties in the τ_h efficiency and energy scale modeling to be treated independently from those for the τ_μ candidates. Systematic uncertainties in the efficiency measurements from the tag-and-probe technique contribute an uncertainty in the total signal yield of 0.5% for the muon trigger efficiency and 1.0–1.4% for each reconstructed muon. The uncertainty in the muon momentum scale is 0.2–5.0%; most muons have $p_T < 100\,\text{GeV}$ and thus an uncertainty of 0.2% [58]. For the τ_h reconstruction, there is an uncertainty in the τ_h identification efficiency of 5–18%, varying with $p_T(\tau_h)$, and an uncertainty in the τ_h energy scale of 1.2–3.0% [63], varying with the number of charged and neutral hadrons in the τ_h decay.

The uncertainty in the luminosity normalization of simulated signal samples is 2.5% [66]. Uncertainty from pileup effects arises from the uncertainty of 4.6% [67] in the total inelastic cross section of pp interactions resulting in a 1% uncertainty in the signal yields. The efficiency correction for the rejection of jets tagged as originating from b quarks contributes an uncertainty of up to 3% in the signal yield.

As described in Section 3, a correction to the simulated ggF signal samples to account for small differences in acceptance for the ggF and VBF H boson production modes contributes a 0.5% uncertainty in the signal yield. Theoretical uncertainties in the H boson production cross section are calculated by varying renormalization (μ_R) and factorization (μ_F) scales independently up and down by a factor of two with respect to the default values with the condition that $0.5 \leq \mu_R/\mu_F \leq 2$. The resulting uncertainties, combined with those from Ref. [46], contribute less than 1% to the overall signal yield uncertainty.

For the background model, the tight-to-loose method contributes a 15% uncertainty in the total expected yield in the signal region. This uncertainty arises from the application of the tight-to-loose ratio to the validation sideband to obtain a prediction for the model shapes in the validation region. The additional uncertainty in the relative normalizations of the low-mass meson resonances arises from differences in the tight-to-loose method predictions of the signal region distributions when derived from the sideband, as discussed in Section 6. This uncertainty is measured to be 5–20% for $\psi(2S)$ and each Υ resonance, which yields up to a 3% uncertainty near these resonances in the final result.

8 Results

The observed distribution of data in the signal region is shown in Figs. 5 and 6. No significant excess of events is observed above the expected SM background. A modified frequentist approach based on the CL criterion [68, 69] is used for upper limit calculations [65] using the LHC test statistic [70]. Systematic uncertainties are represented as nuisance parameters assuming a log-normal PDF in the likelihood fit for uncertainties in the expected yields and a Gaussian PDF of uncertainties in the signal and background model parameters.

Model-independent upper limits at 95% CL are set on $\sigma_H\mathcal{B}(H \to aa \to \mu\mu\tau\tau)/\sigma_{SM}$ and are presented in Fig. 7. Here, σ_{SM} is the SM Higgs boson (or, for $m_H = 300\,\text{GeV}$, σ_{SM} is the SM-like Higgs boson) production cross section including ggF and VBF production modes [46]. Broadly, the sensitivity of this exclusion decreases at low values of m_a because of reconstruction

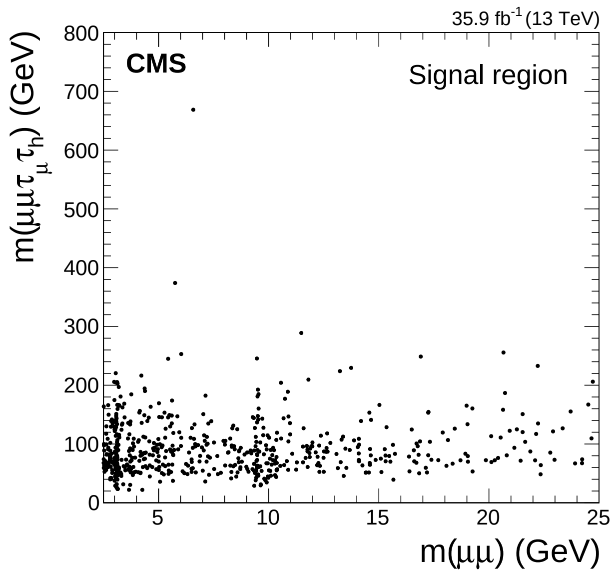

Figure 6: Observed data distribution, as a function of the 4-body visible mass and $\mu\mu$ invariant mass for the signal region; 614 events are observed.

inefficiencies as the decay products of the $\tau\tau$ pair overlap. In addition, for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, as m_{a} increases, the Lorentz boost decreases causing the products to be well separated, failing the requirement of $\Delta R(\tau_{\mu}, \tau_{\mathrm{h}}) < 0.8$. The two peaking structures around $m_{\mathrm{a}} = 10\,\mathrm{GeV}$ are from the Υ resonances where the $\Upsilon(1\mathrm{S})$ resonance is resolvable but the $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ merge because the rejection power of the boosted $\tau_{\mu}\tau_{\mathrm{h}}$ selection sufficiently reduces the number of events in and around these peaks. A third peaking structure is not as apparent but is also present at the $\psi(2\mathrm{S})$ resonance. Comparison with an earlier $\sqrt{s} = 13\,\mathrm{TeV}$ result from the CMS Collaboration [40] targeting resolved $\tau\tau$ decay products is possible for SM Higgs boson decays with $15 < m_{\mathrm{a}} < 21\,\mathrm{GeV}$. In this case, the two approaches have similar sensitivity.

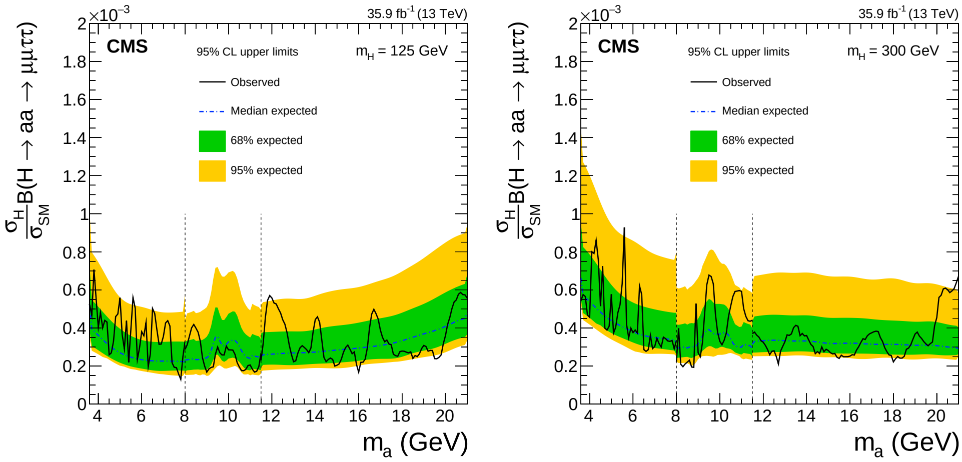

Figure 7: Model-independent 95% CL upper limits on $\sigma_{\mathrm{H}}\mathcal{B}(\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau)/\sigma_{\mathrm{SM}}$ as a function of pseudoscalar boson mass for a Higgs boson with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ (left), and $300\,\mathrm{GeV}$ (right). The vertical dashed lines indicate the transition between the $\mu\mu$ mass fit ranges for a given mass hypothesis, occurring at $m_{\mathrm{a}} = 8$ and $11.5\,\mathrm{GeV}$. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

Upper limits on $\sigma_{\mathrm{H}}\mathcal{B}(\mathrm{H} \to \mathrm{aa})/\sigma_{\mathrm{SM}}$ for the 2HDM+S for each Type-I to -IV as a function of

$\tan\beta$ and m_a are shown in Figs. 8 and 9. The assumed model branching fractions for pseudoscalar decays to $\mu\mu$ and $\tau\tau$ are taken from Ref. [71], and the branching fraction $\mathcal{B}(\mathrm{aa} \to \mu\mu\tau\tau)$ depends strongly on the 2HDM+S type [7]. The branching fractions are calculated in $\tan\beta$ increments of 0.5 above $\tan\beta = 1$ and increments of 0.1 below, and a linear interpolation is applied between the calculated points in Fig. 9. For the Type-I and -II models, we primarily probe the $2m_\tau < m_a < 2m_b$ range, with the Type-I upper limits approximately independent of $\tan\beta$. In the Type-I model, the most stringent limit of 5% is set for $m_a \approx 4.5\,\mathrm{GeV}$. In the Type-III model, this analysis has exclusion power over the full pseudoscalar mass range probed, especially at large $\tan\beta$. For the Type-II and -III models with m_a below the $\mathrm{b\bar{b}}$ threshold, upper limits on $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ are stronger than the 0.47 inferred from combined measurements of SM Higgs couplings [9] for $\tan\beta \gtrsim 0.8$-0.9, becoming as strong as 10% for $\tan\beta \gtrsim 1.5$. In the Type-III models, strong upper limits are set for all pseudoscalar boson masses tested when $\tan\beta \gtrsim 1.5$. The Type-IV model, however, can only be effectively probed in the low-$\tan\beta$ region. For a given m_a, the ratio of decay rates to $\mu\mu$ and $\tau\tau$, respectively $\mathcal{B}(\mathrm{a} \to \mu\mu)$ and $\mathcal{B}(\mathrm{a} \to \tau\tau)$, depends only on m_μ and m_τ [7, 71]. Thus, these results can be converted into upper limits on $\sigma_\mathrm{H}\mathcal{B}(\mathrm{H} \to \mathrm{aa})/\sigma_\mathrm{SM}$. Contours for different $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ values are overlaid. Compared with an earlier result by CMS [40], these upper limits are more stringent (where they can be compared) and extend to lower values of m_a.

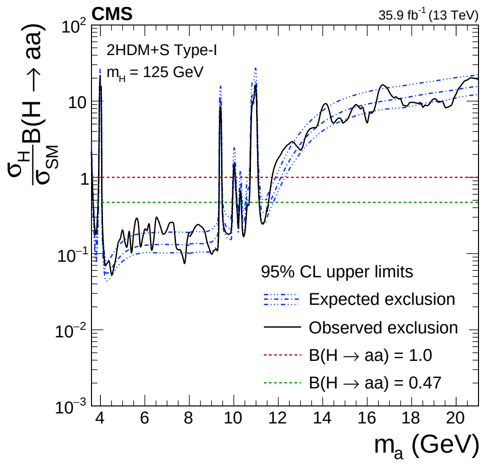

Figure 8: Observed (black) and expected (blue, median and 68%) model-specific 95% CL upper limits on $\sigma_\mathrm{H}\mathcal{B}(\mathrm{H} \to \mathrm{aa})/\sigma_\mathrm{SM}$ as a function of m_a for the Type-I 2HDM+S at $\tan\beta = 1.5$ and $m_\mathrm{H} = 125\,\mathrm{GeV}$. The assumed model branching fractions for pseudoscalar Higgs boson decay to $\mu\mu$ and $\tau\tau$ are taken from Ref. [71] and are approximately independent of $\tan\beta$.

9 Summary

A search for Higgs boson (H) decays to a pair of light pseudoscalar bosons (a) is presented, including the first such LHC results for an H with mass above 125 GeV. The light pseudoscalars decay to $\mu\mu$ and $\tau\tau$ with substantial overlap between the leptons because of the Lorentz boost. This difficult topology motivates the development of a dedicated $\tau_\mu\tau_\mathrm{h}$ reconstruction method to increase the acceptance. Data collected by the CMS Collaboration at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$, are examined and no significant excess over standard model (SM) processes is observed. This analysis obtains model-independent upper limits at 95% confidence level on the branching fraction ($\mathcal{B}$) of a SM-like Higgs boson (H), decaying to a pair of pseudoscalar bosons (a) in the $\mu\mu\tau\tau$ final state, $\sigma_\mathrm{H}\mathcal{B}(\mathrm{H} \to \mathrm{aa} \to \mu\mu\tau\tau)/\sigma_\mathrm{SM}$, as well as model-specific upper limits on $\sigma_\mathrm{H}\mathcal{B}(\mathrm{H} \to \mathrm{aa})/\sigma_\mathrm{SM}$

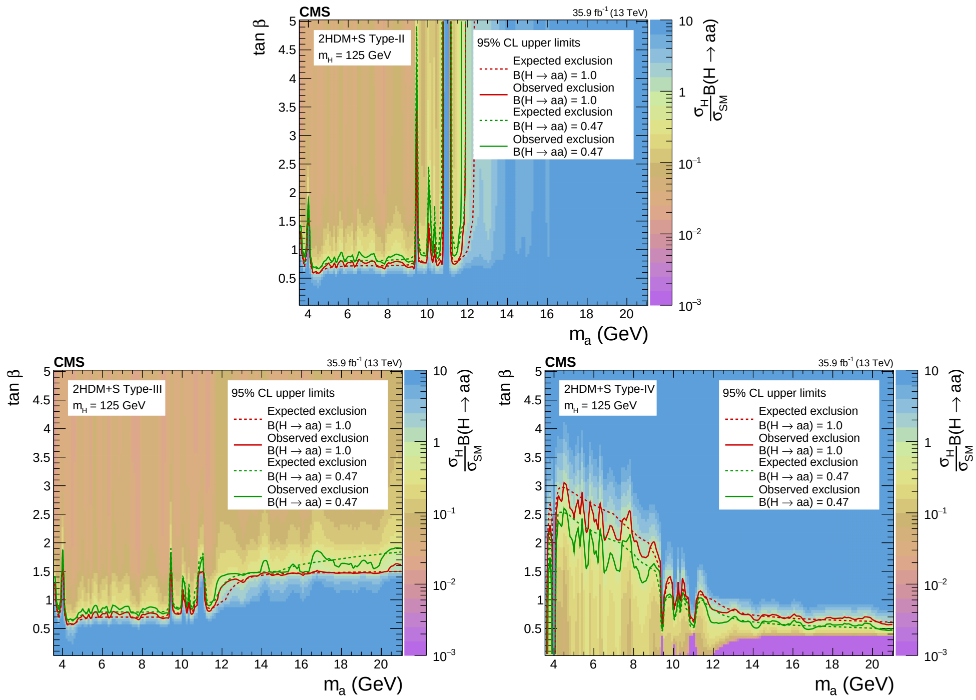

Figure 9: Model-specific 95% CL upper limits on $\sigma_{\mathrm{H}}\mathcal{B}(\mathrm{H} \to \mathrm{aa})/\sigma_{\mathrm{SM}}$ for three model types of the 2HDM+S as a function of $\tan\beta$ and m_{a}, for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$. Contours for two values of $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ are shown for reference. The assumed model branching fractions for pseudoscalar Higgs boson decay to $\mu\mu$ and $\tau\tau$ are taken from Ref. [71].

for Type-I, -II, -III, and -IV two Higgs doublets plus singlet models. In the Type-I model, the upper limit on the allowed branching fraction is approximately independent of $\tan\beta$, with the most stringent limit of 5% set for $m_{\mathrm{a}} \approx 4.5\,\mathrm{GeV}$. For the Type-II and -III models with m_{a} below the $\mathrm{b\overline{b}}$ threshold, upper limits on $\mathcal{B}(\mathrm{H} \to \mathrm{aa})$ are stronger than the 0.47 inferred from combined measurements of SM Higgs couplings for $\tan\beta \gtrsim 0.8$-0.9, becoming as strong as 10% for $\tan\beta \gtrsim 1.5$. In the Type-III models, the predicted branching fraction to leptons increases with $\tan\beta$, leading to strong upper limits for all pseudoscalar boson masses tested when $\tan\beta \gtrsim 1.5$. In contrast, the strongest upper limits for Type-IV models are set when $\tan\beta < 1$. These results significantly extend upper limits obtained by earlier searches by the CMS and ATLAS Collaborations, such as those obtained by CMS with 8 TeV data [39], and are complementary to present searches (e.g. Ref. [40]) at higher m_{a} that lead to resolved $\mu\mu$ and $\tau\tau$ final states.

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38: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
39: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
40: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
41: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
42: Also at Institute for Nuclear Research, Moscow, Russia
43: Now at National Research Nuclear University 'Moscow Engineering Physics Institute'

(MEPhI), Moscow, Russia
44: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
45: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
46: Also at University of Florida, Gainesville, USA
47: Also at Imperial College, London, United Kingdom
48: Also at P.N. Lebedev Physical Institute, Moscow, Russia
49: Also at California Institute of Technology, Pasadena, USA
50: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
51: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
52: Also at Università degli Studi di Siena, Siena, Italy
53: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
54: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
55: Also at National and Kapodistrian University of Athens, Athens, Greece
56: Also at Universität Zürich, Zurich, Switzerland
57: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
58: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
59: Also at Şırnak University, Sirnak, Turkey
60: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
61: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
62: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
63: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
64: Also at Mersin University, Mersin, Turkey
65: Also at Piri Reis University, Istanbul, Turkey
66: Also at Adiyaman University, Adiyaman, Turkey
67: Also at Ozyegin University, Istanbul, Turkey
68: Also at Izmir Institute of Technology, Izmir, Turkey
69: Also at Necmettin Erbakan University, Konya, Turkey
70: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
71: Also at Marmara University, Istanbul, Turkey
72: Also at Milli Savunma University, Istanbul, Turkey
73: Also at Kafkas University, Kars, Turkey
74: Also at Istanbul Bilgi University, Istanbul, Turkey
75: Also at Hacettepe University, Ankara, Turkey
76: Also at Vrije Universiteit Brussel, Brussel, Belgium
77: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
78: Also at IPPP Durham University, Durham, United Kingdom
79: Also at Monash University, Faculty of Science, Clayton, Australia
80: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
81: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
82: Also at Bingol University, Bingol, Turkey
83: Also at Georgian Technical University, Tbilisi, Georgia
84: Also at Sinop University, Sinop, Turkey
85: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
86: Also at Nanjing Normal University Department of Physics, Nanjing, China

87: Also at Texas A&M University at Qatar, Doha, Qatar
88: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea